Renewable and Sustainable Energy Reviews 35 (2014) 311–317

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Reduction of cooling water consumption due to photovoltaic and wind electricity feed-in

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ARTICLE INFO

Article history:
Received 21 January 2014
Accepted 7 April 2014
Available online 25 April 2014

Keywords:
Water use
Cooling water
Renewable energies
Photovoltaic
Wind
Water/energy interactions
Water management

ABSTRACT

In Germany, in the coming decades, nuclear and some coal power plants shall be substituted mainly by photovoltaic (PV) and wind turbines. In this study the impact of PV+wind electricity feed-in on the operation of thermoelectric power plants and the corresponding water consumption was analyzed for July 2011–June 2013. Using hourly time-series of electricity demand, feed-in by renewables, and net export of power abroad, cycling of all thermoelectric power plants along the River Neckar was simulated and the corresponding cooling water amount was calculated. The study show that the electricity generation by PV+wind results in a 7% reduction of cooling water consumption, that equals 43 l per total MWh. The substitution of coal power plants by PV+wind is highest in spring and autumn due to a coincidence of medium-high electricity demand and high electricity feed-in by PV+wind. Water consumption reduction varies seasonally between 4% and 11%. Over one day a maximum of 28,690 m^3 less water was consumed due to PV+wind feed-in.

By 2050 the targeted share of renewables is about 80% (fourfold feed-in by PV+wind), that corresponds to a roughly estimated 70% reduction of water consumption. This reduction help to alleviate low flow situations and decrease water temperature but might be offset by climate change impacts.

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http://dx.doi.org/10.1016/j.rser.2014.04.029
1364-0321/

1. Introduction

Thermoelectric power plants require large amounts of water to cool their steam cycle. In Germany, in 2010 approximately 63% of total freshwater abstracted was used in the energy sector, 99% of which was for cooling purposes. In the federal state Baden–Württemberg the proportion of abstracted water for power plant cooling was even higher at 76% [4].

The cooling process is generally associated with a specific water consumption, as extensively reviewed by [8]. Furthermore, the elevated temperature of discharged cooling water may have significant impacts on the receiving river ecosystem. These include the destruction of vegetation, increased oxygen depletion, algae growth, the extinction of heat intolerant species, and the expansion of exotic or pest fish or other fauna suited to elevated temperatures [e.g. [6]]. In Germany, nearly all thermoelectric power plants are located adjacent to large rivers. In late summer and autumn, when river flow and/or water temperatures reach certain thresholds, thermoelectric power plant discharges have to be curtailed according to official regulations. This reduction in output, however, may result in power shortages and thus negative economic impacts. During the drought of August 2003 (foreshadowing potential climate change impacts) water use was severely restricted due to low flow and unsustainably high water temperatures, such that nearly all large thermoelectric power plants had their output curtailed.

In the future, one consequence of climate change may be lower river discharges and higher water temperatures in late summer. Thermoelectric power plants are highly vulnerable to these changes not only because of their high water demand but also due to the restricted transport of coal by river during low flow [11]. Furthermore, the future development of the electricity sector, especially power demand and the electricity generation mix, will have important implications for regional water resources [9,2,3]. Since the implementation of the German Renewable Energy Act in 2000 a very large expansion of biomass, photovoltaic (PV), and wind power plants has occurred. In Baden–Württemberg, the share of renewable energy sources (RES) in power generation increased from 9% in 2004 to 20% in 2011, mainly due to on-going new installations of PV and biogas power plants. In December 2012 the installed PV power plants corresponded to a total 4300 MW_{peak} generation capacity, equivalent to 0.4 kW per person, and approximately 7% of total electricity generation. The number of wind turbines did not increase so strongly, this was due to limited acceptance among the population, and currently stands at about 1% of the generation mix in Baden–Württemberg. In the aftermath of the 2011 Fukushima nuclear disaster in Japan, the subsequent political turnaround in Germany has resulted in a goal for 2020 that PV and wind should have a share of 12% and 10% of the energy mix, respectively.

Until now, the relationship between power supply from non-thermal RES and water consumption by conventional power plants has scarcely been analyzed. Kyle et al. [7] and Clemmer et al. [2] provided future scenarios with a higher share of RES in the electricity generation mix. However, only annual water amounts were calculated based on hypothetical situations. We present a model (PVW^2) which simulates the output reduction of thermoelectric power plants in relation to PV+wind feed-in, and thereby the reduced cooling water consumption, based on hourly power demand and PV+wind feed-in data. Although this study focuses on energy supply in Baden–Württemberg and water use along the River Neckar, the model presented is applicable to other water bodies and some figures calculated can be transferred to other regions. The results are of particular relevance to policy and decision makers in regions with an expected increase of power demand and a threat of water scarcity.

2. Cooling water consumption

Thermoelectric power plants need large amounts of cooling water to condense steam after its passage through the turbines. Three general types of cooling systems can be distinguished, and are associated with different water consumption and heat input into the receiving water body [5,1]. Once-through systems use the water once before discharging it back into the river or lake. Here, the higher temperature of the discharged water leads to a higher evaporation rate in the water body and therefore to cooling-induced water consumption. Wet recirculating systems reuse cooling water multiple times. In these systems cooling towers are normally used to dissipate heat from cooling water to the atmosphere: warm cooling water sprinkles through the lower part of a natural, or mechanically induced, draft cooling tower and evaporates. This process has a higher evaporation rate than for a once-through cooling system, but the total volume of water withdrawn and the warming of the water body, per unit electricity generated, is lower. The third type of cooling system is the dry recirculating system, which needs and consumes no water and the steam-carrying pipes are cooled by ventilation. Dry, and also some wet, recirculating cooling systems require much more energy than once-through systems.

Most power plants operate a combination of the aforementioned cooling methods depending on site-specific conditions and official approvals. Once-through systems are often equipped with a cooling tower, which reduces the temperature of the water discharged. In so-called hybrid cooling systems both wet and dry cooling components are used either separately or simultaneously.

Mean water consumption rates for German power plants, are relatively low compared to other countries (Table 1). For example, in the USA the water consumption of coal power plants with wet recirculation and cooling towers averages 1.8 m^3/MWh [5]. Dry-cooling systems consume no water and are not used in Germany, and are thus not listed in Table 1. German power plants with combined-cycle gas turbines use a once-through cooling system and are not equipped with cooling towers or hybrid cooling systems.

3. Relationship between power generation by non-thermal renewable energy sources and water consumption

According to the German Act on Granting Priority to Renewable Energy Sources transmission system operators are obliged to take the electricity feed-in by renewable energy sources (RES) in priority to electricity generated from conventional power plants. Thus, if the electricity generation by PV and/or wind is high, the “load-following” power plants and even some base-load power plants curtail their output to a certain extent. This reduction in generation results in a reduction of cooling water consumption. In this study “consumption” refers to the amount of water lost to evaporation, and is, hence, not discharged back to the water body. The lower water consumption due to electricity feed-in by photovoltaic and wind is referred to as “consumption reduction”.

Table 1
Mean water consumption for German power plants given in m^3/MWh [[5]].

Cooling system	Coal	Nuclear	Combined-cycle
Once-through	0.90	1.44	0.47
Once-through with cooling tower	1.19	1.87	–
Wet recirculating with cooling tower	1.33	2.12	–
Wet and dry recirculating (hybrid)[a]	0.97	1.58	–

[a] Proportion of dry cooling = 30% is assumed.

3.1. Approach of the model PVW^2

To quantify consumption reduction, a mathematical model (PVW^2) was developed. For a given set of assumptions the cooling water consumption of all thermoelectric power plants along a particular river can be calculated for a particular network load situation. As input data, time-series of network load, and electric feed-in by photovoltaic and wind, are required. For biomass and hydropower average base load feed-in is used. Furthermore, capacity, cycling modes and the type of cooling system is needed for each thermoelectric power plant along the river in question.

Generally, total electricity generation has to be equal to total electricity demand, i.e. more or less equal to the network load. In PVW^2, the feed-in by RES is subtracted from the network load, the residual load is assumed to be delivered by conventional power plants. The actual cooling water consumption of a particular power plant is derived from its actual performance (Table 1). For instance, if a coal power plant reduces its output by 40% in response to a high feed-in by PV, the water consumption is also reduced by 40%. The consumption reduction results from the difference in water consumption with and without wind and photovoltaic feed-in. Finally, the consumption reduction at all power plants along the river is added and various indices, such as maximum consumption reduction or total consumption reduction per year can be calculated.

3.2. Simulation of power plant operation

The operation of a conventional power plant depends on the actual electricity demand, the type (e.g. nuclear, coal, gas) and age of the station. In the model, different power plant types are brought online according to their merit order, which ranks the power plants in ascending order of their marginal costs of production. That means the residual load is met first by cost-efficient nuclear power plants, then by coal power plants, and finally, by the most cost-intensive peak load plants such as combined-cycle and gas power plants (Fig. 1). The order of the power plants within one of these groups depends on the age of the power plants. E.g. the older coal power plants with lower efficiency are only in operation when the newer ones are already operating at full capacity. Or conversely, the oldest gas-fired power plant is shut off first when the peak load decreases.

Cycling is simulated under certain assumptions (Fig. 1): if the feed-in of RES is higher than the actual electricity demand (residual load ≤ 0), nuclear power plant output is curtailed to 80% of capacity. If the residual load is between 0 and 2000 MW, coal-fired plants are cycled between 40% and 100% of their capacity in proportion to actual electricity demand. Since newer coal-fired power plants allow for more flexible operation than older ones, the minimum load of younger coal power plants is 20% whereas the older stations are completely shut off when residual load ≤ 0. Finally, peak-load power plants (e.g. gas and oil) run either on full capacity or are completely shut off. Marketing aspects are not considered in the model.

4. Application of PVW^2 to the river Neckar

4.1. Hydrology and water use in the Neckar basin

The River Neckar has a basin area of about 14,000 km^2, is 367 km in length, and is a major tributary of the River Rhine. Its headwaters are in the Black Forest at an elevation of around 706 m a.m.s.l., and it passes through the densely populated, heavily industrialized region of Stuttgart and Heilbronn before reaching the Rhine near Mannheim at 95 m a.m.s.l. The mean annual flow is

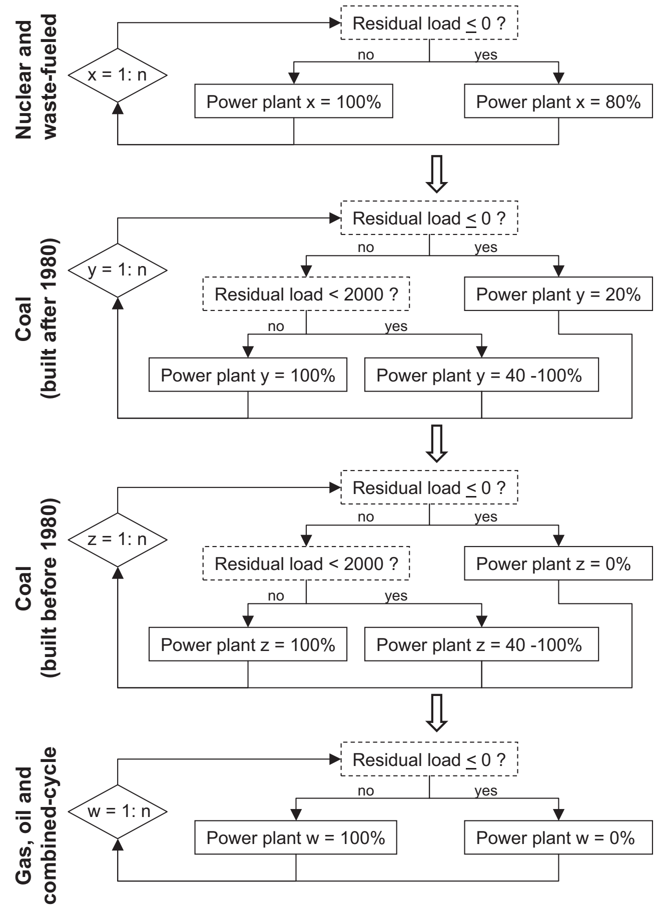

Fig. 1. Operation and cycling of power plants for actual residual load (x, y, z, and w: specific power plants within the power plant group; n: number of power plants in the power plant group). Initial residual load is the network load minus electricity feed-in by RES minus net-export of electricity.

145 m^3/s at Mannheim. The mean areal precipitation of around 700 mm/yr is rather low due to the basin being in the rain shadow of the Black Forest.

The Neckar is one of the most intensely used rivers in Europe; one nuclear power plant and two coal power plants with a total capacity of 3.6 GW are located along the Neckar to supply the energy demands of Stuttgart alone. Due to restricted water use on the Neckar which occasionally suffers with ecologically unsustainable high water temperatures, power plant operators have ongoing programmes to improve their water use efficiency. For instance, the uppermost large coal-fired power plant, Altbach–Deizisau, was the first power plant in Germany to be equipped with hybrid cooling towers.

4.2. Data sources and preprocessing

In Germany, due to the transparency requirement of the Renewable Energy Act and the warranty of open market participation, time-series of power transmission, network load, and feed-in by RES are freely available on the internet. The transmission system operator TransnetBW is responsible for the area of Baden–Württemberg, and data from their website (www.transnetbw.de/downloads-and-informationen/) was used in our simulations of the correlation between PV+wind feed-in and the operation of thermoelectric power plants along the Neckar.

Model input data includes hourly time-series values of network load, PV+wind feed-in, as well as, power export and import to/from abroad, for the period June 2011–July 2013. For PV we used

PV electricity that is generated exclusively in Baden–Württemberg. But to quantify the feed-in by wind, data for whole Germany were used: the total German wind power was multiplied by 0.13 since the share of the Baden–Württemberg's network load in total German network load is 13% according to the European Network of Transmission System Operators for Electricity (www.entsoe.eu/db-query/consumption/mhlv-a-specific-country-for-a-specific-month/). For hydropower and biomass constant values were assumed based on mean annual values given by the Statistical Office (www.statistik.baden-wuerttemberg.de/UmweltVerkehr/); in 2011 mean feed-in by hydropower was 466 MW and 360 MW for biomass (mean values for Baden–Württemberg). The net export of power abroad was calculated by the load flows to and from France, Switzerland and Austria.

In addition to time-series data, the characteristics of each thermoelectric power plant; type, age, capacity, cooling system, and corresponding water consumption have to be defined. This information was supplied by the Federal Network Agency (www.bundesnetzagentur.de/DE/ Sachgebiete/ElektrizitaetGas/Sonderthemen/Kraftwerksliste/), and by personal request.

Table 2
Reduction of cooling water consumption due to PV+wind feed-in.[a]

Time period	Mean water consumption reduction		
	(%)	($m^3 \times 10^6$)	(m^3/d)
Total year	6.8	3.02	8300
October–December	4.3	0.51	5580
January–March	3.5	0.43	4718
April–June	10.7	1.08	11,930
July–September	9.9	1.00	10,970

[a] Calculated for July 2011–June 2013 (maximum network load: 12.4 GW; maximum power by wind: 10 GW; power by PV: 3.2 GWpeak in 2011 to 4.6 GWpeak in 2013)

4.3. Results for the river Neckar

The substitution of thermoelectric power plants by PV+wind feed-in, results in a 7% reduction in water consumption from the Neckar, corresponding to 3 million m³ less water per year for an annual power generation of 70,000 GWh (including net-export abroad). The mean annual PV feed-in was 4080 GWh, the mean annual wind feed-in was 5970 GWh. Between April and September the water consumption reduction is generally greatest (Table 2) due to medium-high electricity demand and high PV+wind feed-in. During low flow conditions (July–September) the coincidence of peak network load and peak (midday) PV generation is beneficial for cooling water demand as shown in the following examples.

In autumn 2011 critical low flow occurred on the Neckar and the official low flow threshold was reached several times. Due to PV+wind feed-in of up to 4000 MW at peak power demand, coal power plants could be curtailed and less water was consumed for cooling (Fig. 2). On 15th Sept 2011 (Thursday) the Neckar discharge was for the first time below the low flow threshold. On this day the reduction of cooling water consumption was 0.39 m³/s equivalent to 25%. Over the whole day 16,500 m³ less water was consumed.

The greatest reduction in water consumption in the period July 2011–June 2013 was achieved on 14th Sept 2012 and 18th April 2013 (Fig. 3). Here, the reduction was 0.61 m³/s, or 40% of water consumption without PV+wind feed-in. On 18th April 2013 (Thursday) a total of 28,690 m³ less water was consumed.

In June and July when solar radiation is around its maximum, network load is also low, and the very high PV feed-in is sometimes too high for the actual operation mode of the thermoelectric power plants (Fig. 3). In contrast, in winter the network load is so high, that reduction of water consumption can only be reached when the feed-in by wind is very high. Thus, in most winter weeks thermoelectric power plants could not be curtailed (Fig. 4).

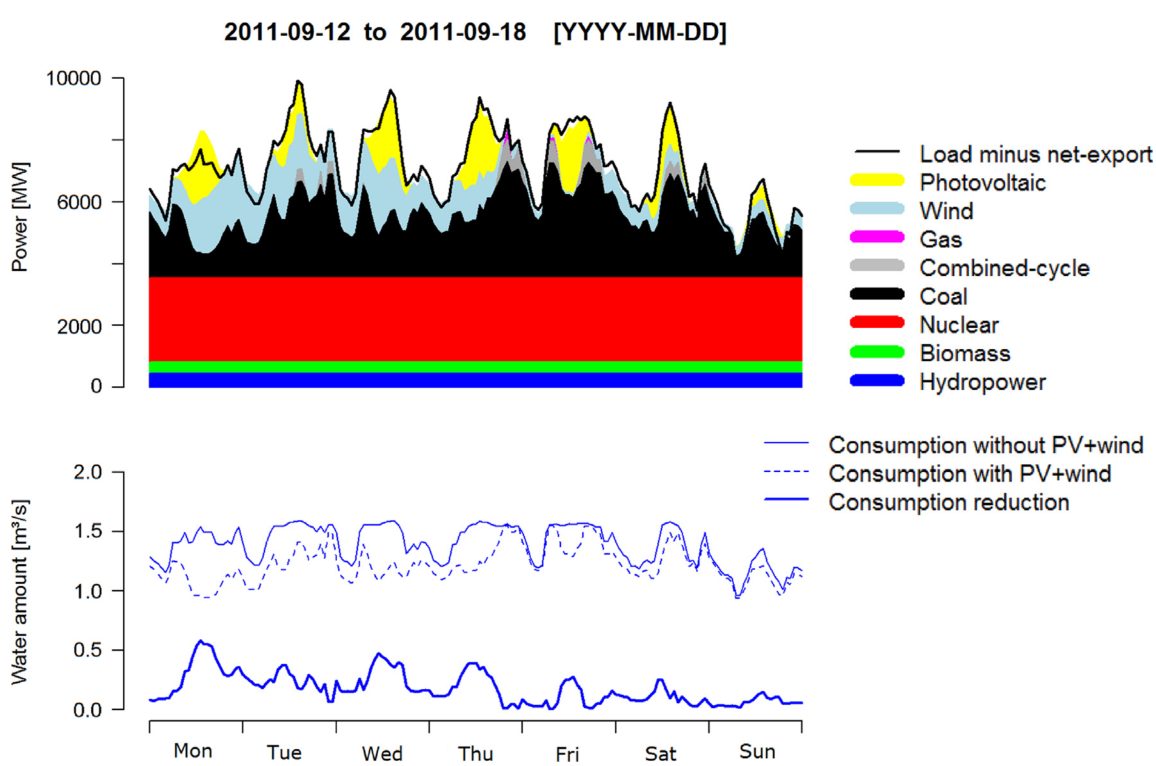

Fig. 2. Critical low flow conditions in Sept 2011. Feed-in by RES and operation of thermoelectric power plants for all Baden–Württemberg (upper graph) and corresponding cooling water consumption on the River Neckar (lower graph) for one week.

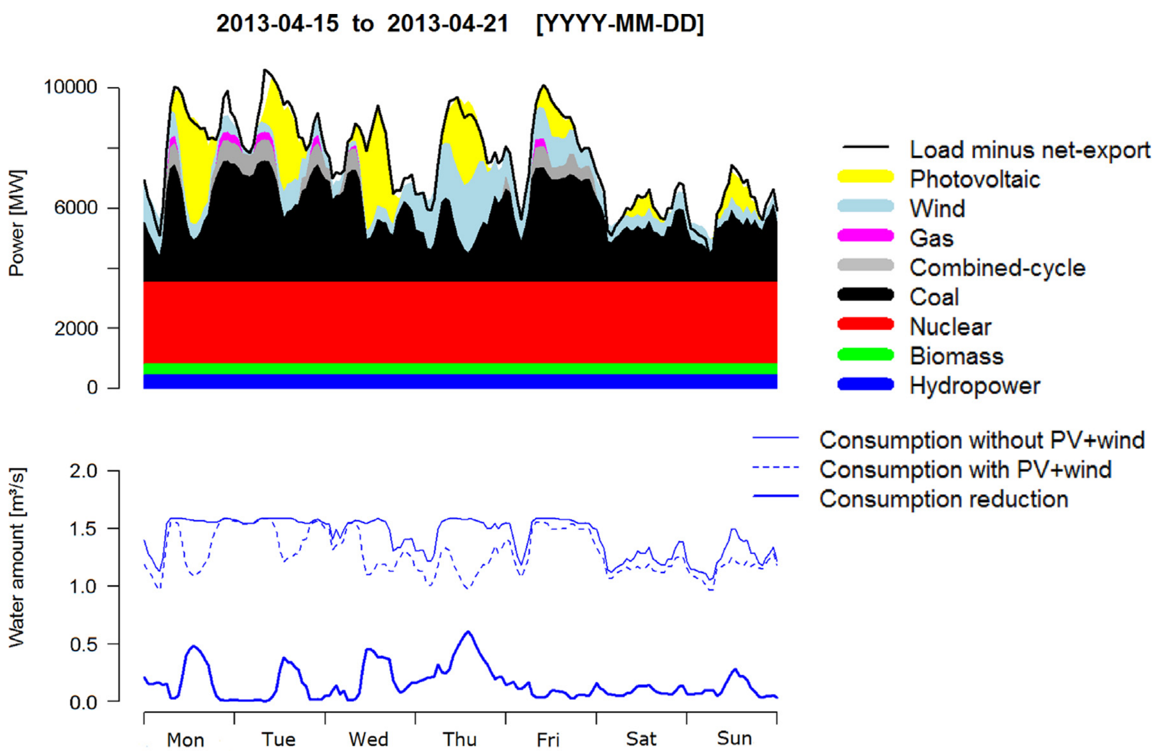

Fig. 3. Highest reduction of water consumption in April 2013. Feed-in by RES and operation of thermoelectric power plants for all Baden–Württemberg (upper graph) and corresponding cooling water consumption on the River Neckar (lower graph) for one week.

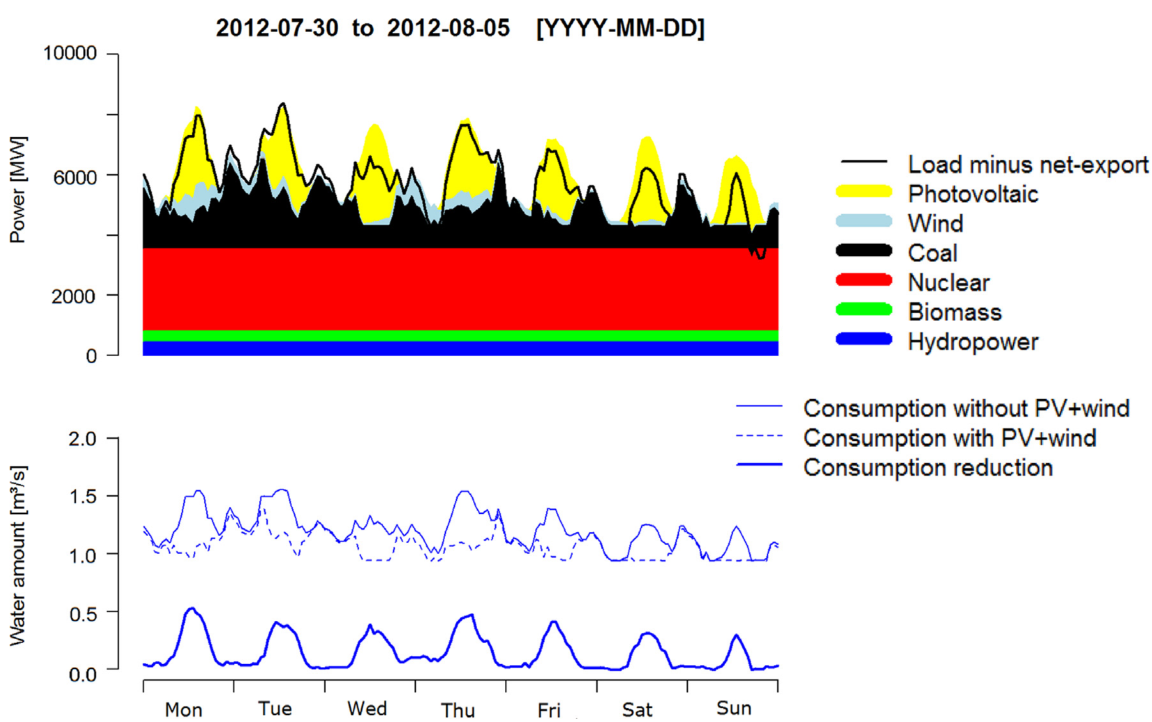

Fig. 4. High feed-in by PV in July/August 2013. Feed-in by RES and operation of thermoelectric power plants for Baden–Württemberg (upper graph) and corresponding cooling water consumption on the River Neckar (lower graph) for one week.

5. Discussion

5.1. Relevance of reduced water consumption on the Neckar

The feed-in by PV+wind results in lower cooling water consumption especially in spring and late summer, which helps to mitigate competing water use on the Neckar. However, because of the existing water-saving cooling systems of the larger power plants, the consumption reduction is relatively small compared to the discharge of the Neckar. The maximum reduction (all water consuming power plants are shut off) is about 1.6 m³/s; less than 10% of the lowest ever measured discharge of the Neckar.

The occurrence of reduced water consumption is also associated with higher water temperatures, which are ecologically significant especially in late summer. Here, a beneficial side-effect of high midday PV feed-in (when electricity demand is also high), which curtails thermal power plants, is that it reduces not only the water consumption but also the heat input to the river, which is crucial over the midday period.

The lower 200 km of the Neckar is navigable for freight shipping and has 29 locks equipped for hydroelectric generation with a total output of around 100 MW. During low flow conditions any increase in discharge is beneficial both for hydropower generation and navigability. The calculated maximum consumption reduction (1.6 m^3/s, as mentioned above) provides a small boost to the total hydropower generation of around 1.4 MW, equivalent to the performance of a medium-size wind turbine.

5.2. Assumptions and plausibility of the model approach

The operating mode of a power plant depends on many factors. In the approach used here, power plant operation is simulated according to actual residual load (electricity demand minus feed-in by RES). Generally, one has to keep in mind, that electricity does not stop at federal or national borders but spreads along the transmission grid depending on its physical parameters. Thus, electricity that is generated in Baden–Württemberg by PV is not necessarily used locally but may supply other German transmission system operators as well as going abroad. Conversely, offshore wind generated power may not reach Baden–Württemberg as assumed (13%) due to insufficient grid capacity. Import and export abroad is incorporated in the model (as mentioned above), but no data are available concerning the load flow to the other three German transmission system operators. Thus, the calculation of the residual load is less realistic when PV and/or Wind feed-in is high.

Furthermore, in some cases it is economically preferable to cut out wind and PV instead of "cycling" coal or even nuclear power plants; these and older coal-fired plants are generally not designed for cycling but for base load, and repeated cyclic operation can be damaging to plant equipment [10]. The corollary of this is that the changes in power plant operation simulated by the model are probably exaggerated, and are in reality less frequent. A further simplification in the PVW² model is that pumped-storage hydropower plants and power plant shut-downs for upgrading or maintenance are not included. Both aspects may have a strong impact on the hourly model calculations but their effects would be integrated-out over longer-term assessments. Additional uncertainties arise from the assumed quantities of cooling water for a specific cooling system. The values in Table 1 are relatively small compared to those reported by Macknick et al. [8] and Davies et al. [3]. For a hybrid cooling system the volume of water consumed depends on the share of dry cooling, which is set at 30% in this study but is not constant in reality.

Since other investigations into the relationship between electricity generation and water consumption [e.g. [13,12,9,7]] were mainly focussed on annual timesteps, the higher temporal resolution simulated by PVW² allows for a more detailed and realistic representation, and a discussion of seasonal effects as well as single low flow situations, which is of greater relevance for water body management and river ecological health.

5.3. Future perspectives

In Germany, the rapid expansion of RES, especially wind and PV, will continue in the coming decades. In 2022, all nuclear power plants must be shut down according to recent political regulation. By 2022 electricity demand will have to be met mainly by RES, coal and gas. By 2050 the targeted share of RES is about 80%, and the electricity demand is expected to remain more or less constant, consequently cooling water use should decline sharply over the coming decades. We projected the PVW² model to 2050 and roughly estimated a 70% water consumption reduction (assumptions: nuclear power plant shut down and fourfold PV+wind feed-in). One of the four US electricity supply/water use scenarios presented by Macknick et al. [9] (scenario 4) is very similar to the German prognosis; electricity generation by RES increases from 10% in 2010, 50% in 2035, and 80% in 2050, the concurrent shut-down of coal and nuclear plants results in an 85% reduction in water consumption by 2050.

This reduced water consumption might, however, be offset by climate change impacts (i.e. higher temperatures, longer droughts). Furthermore, in autumn at times when the share of RES is small (e.g. in windless nights), and electricity demand is high (e.g. due to cold weather), and river flow after a very dry summer very low, the achievement of any reduction in water consumption may still prove to be a challenge.

In countries with an anticipated explosion in electricity demand, such as China and India, water use for cooling purposes is expected to grow tremendeously. In China, for instance, [3] calculated an increase of water consumption by 2095 of between 224% and 450%. While water withdrawal rates per MWh are expected to decrease, total water consumption volume will increase due to the switch from once-through cooling systems to wet recirculating cooling systems with higher evaporation. Thus, the deployment and application of water conservation technologies, as well as the water-saving benefits of RES, should be an important consideration of future energy and water management decisions, especially in regions where water scarcity is already a problem.

6. Conclusions

We presented a simulation of the effect of PV+wind feed-in on the cycling of thermoelectric power plants, and the consequent reduction of cooling water consumption. For the calculations, actual measured hourly time-series of electricity demand and feed-in by renewables were used. The high temporal resolution used in our investigations facilitates an assessment of previously unavailable water consumption rates for different seasons as well as specific situations such as critical low flow, or high energy demand. The results of the case study for the river Neckar show that water consumption reduction is generally highest in spring and autumn due to a combination of elevated (but not too high) electricity demand and high electricity feed-in by PV+wind. In summer, high solar radiation often coincides with high electricity demand (midday peak), low river flow, and high water temperatures. However, since daily electricity demand is much lower in the summer (June–August) than in winter, coal-fired power plants are curtailed in any case, or even completely shut-down, meaning that potential water consumption reduction is relatively small.

In the future, however, low flow situations in autumn are likely to be most vulnerable to competing water demands. The rapid growth in renewables over the coming decades will help to alleviate low flow situations, decrease water temperatures, and may also slightly enhance hydropower output.

Acknowledgment

This study was funded by the federal state of Baden–Württemberg (Zukunftsoffensive III) within the project KLIMOPASS (Climate change and model based adaptation strategies in Baden–

Württemberg; project management agency: LUBW). We gratefully acknowledge the very valuable contribution of Sebastian Raiber und Henriette Kammer and their initial ideas. Furthermore, the discussion with affected companies was very helpful. We are also indebted to Jeremy Wilkinson for his thoughtful review, and to Alexander Loris for his assistance at various stages.

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